Disappearing tracks at Muon Collider

José Francisco Zurita
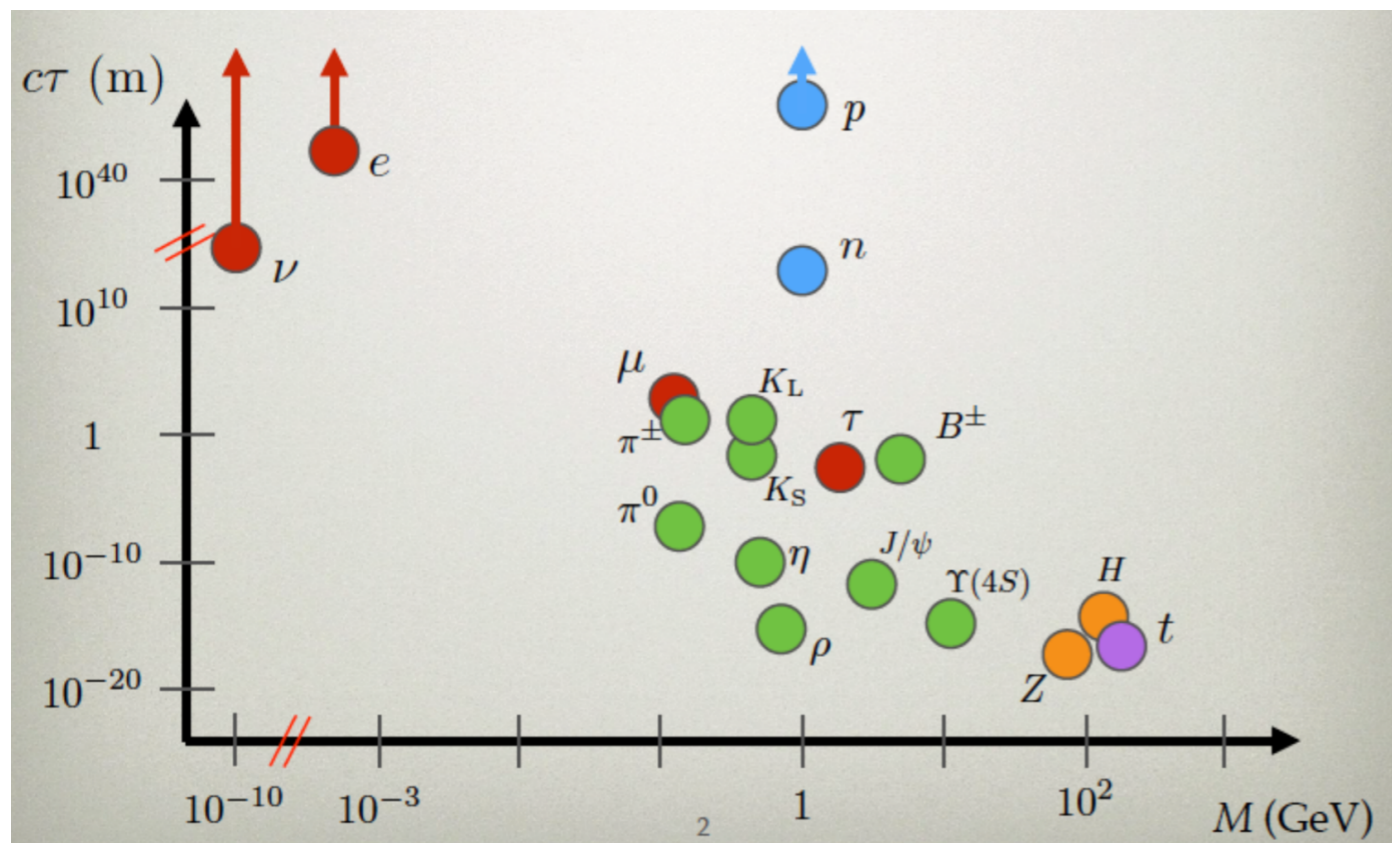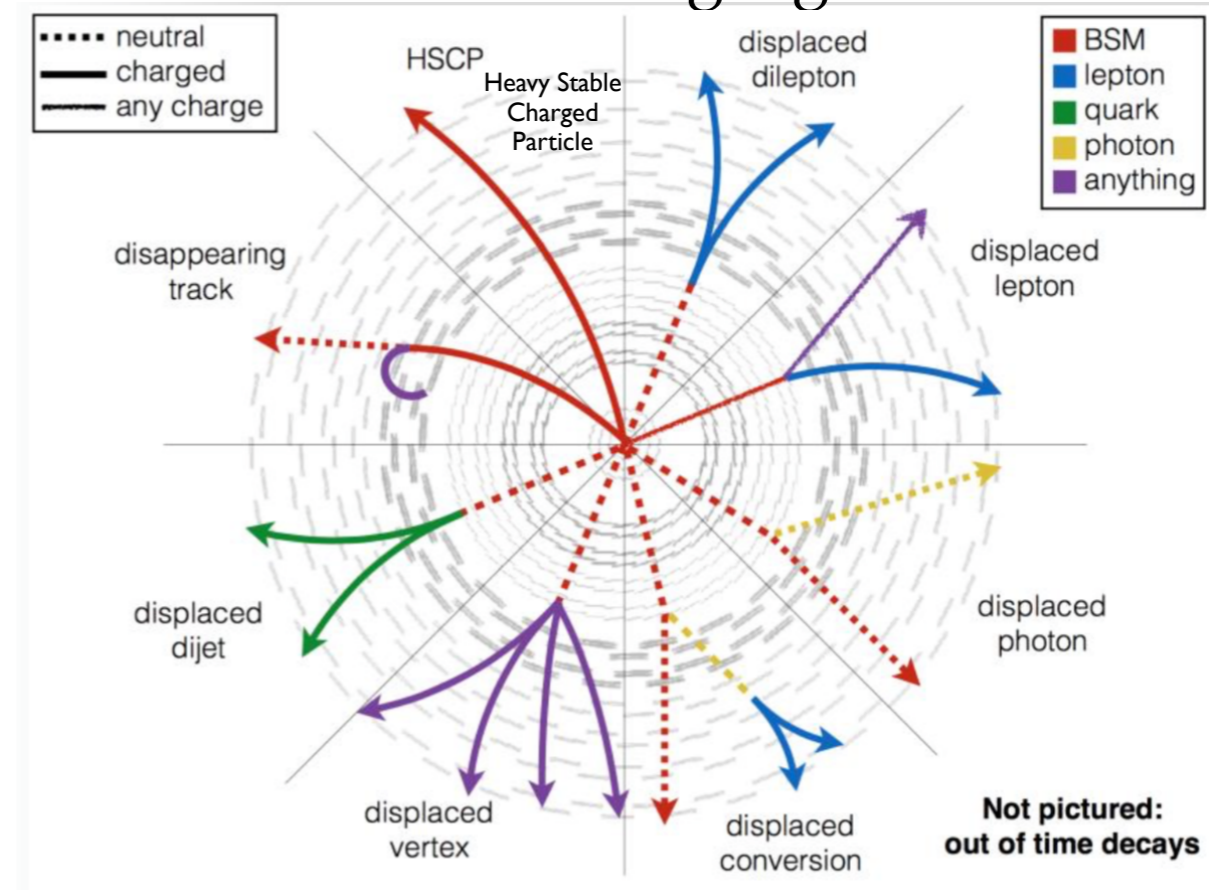
Energy Frontier Workshop - Restart, Zoom, 02.09.2021

Long-Lived Particles

- LLPs: New Particles with macroscopic lifetimes ($\tau \sim$ ns, $c\tau \sim$ cm), theoretically well motivated.
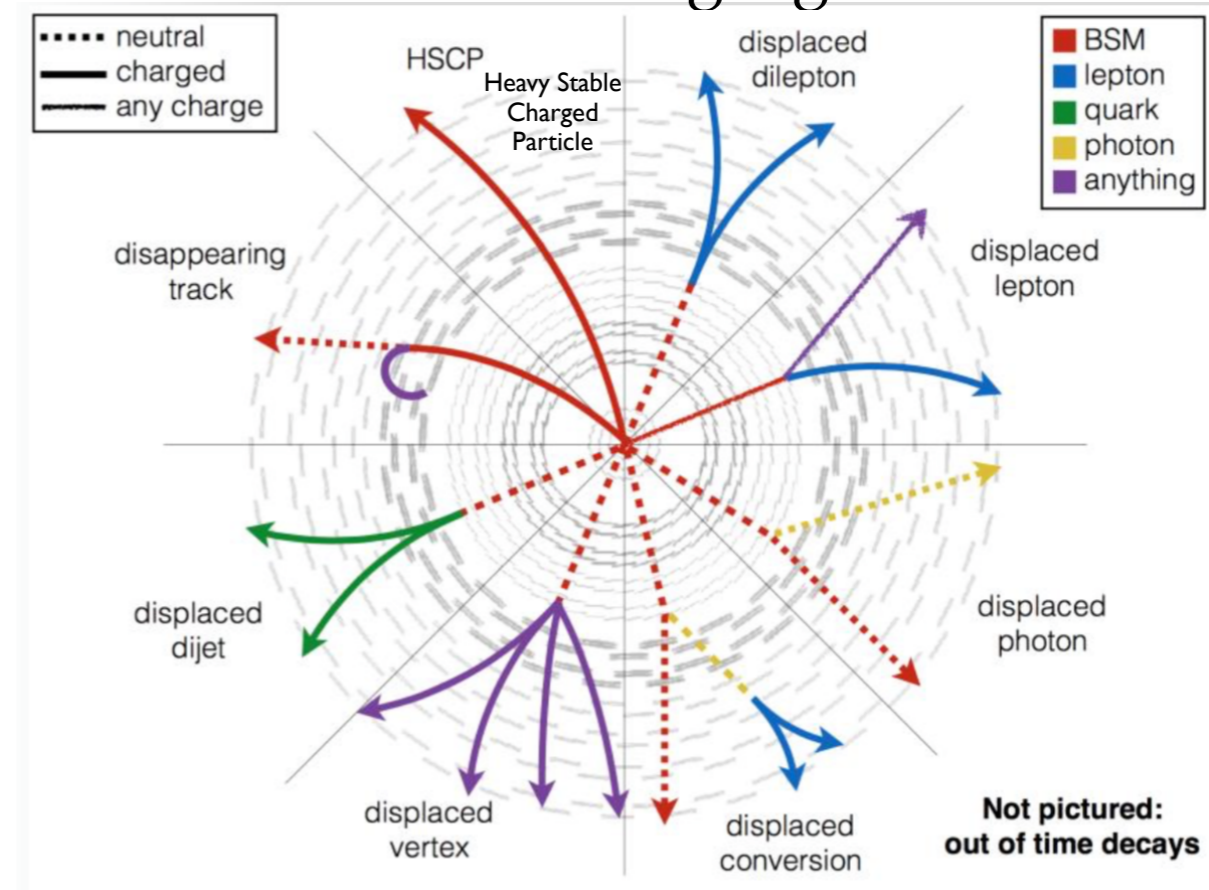
Exist in the SM!

A lot of interesting signatures!

large $c\tau$, small Γ

- Large mass hierarchies
- Compressed spectra
- Small couplings

EW Baryogenesis
Dark Matter
Hierarchy Problem
Neutrino Masses

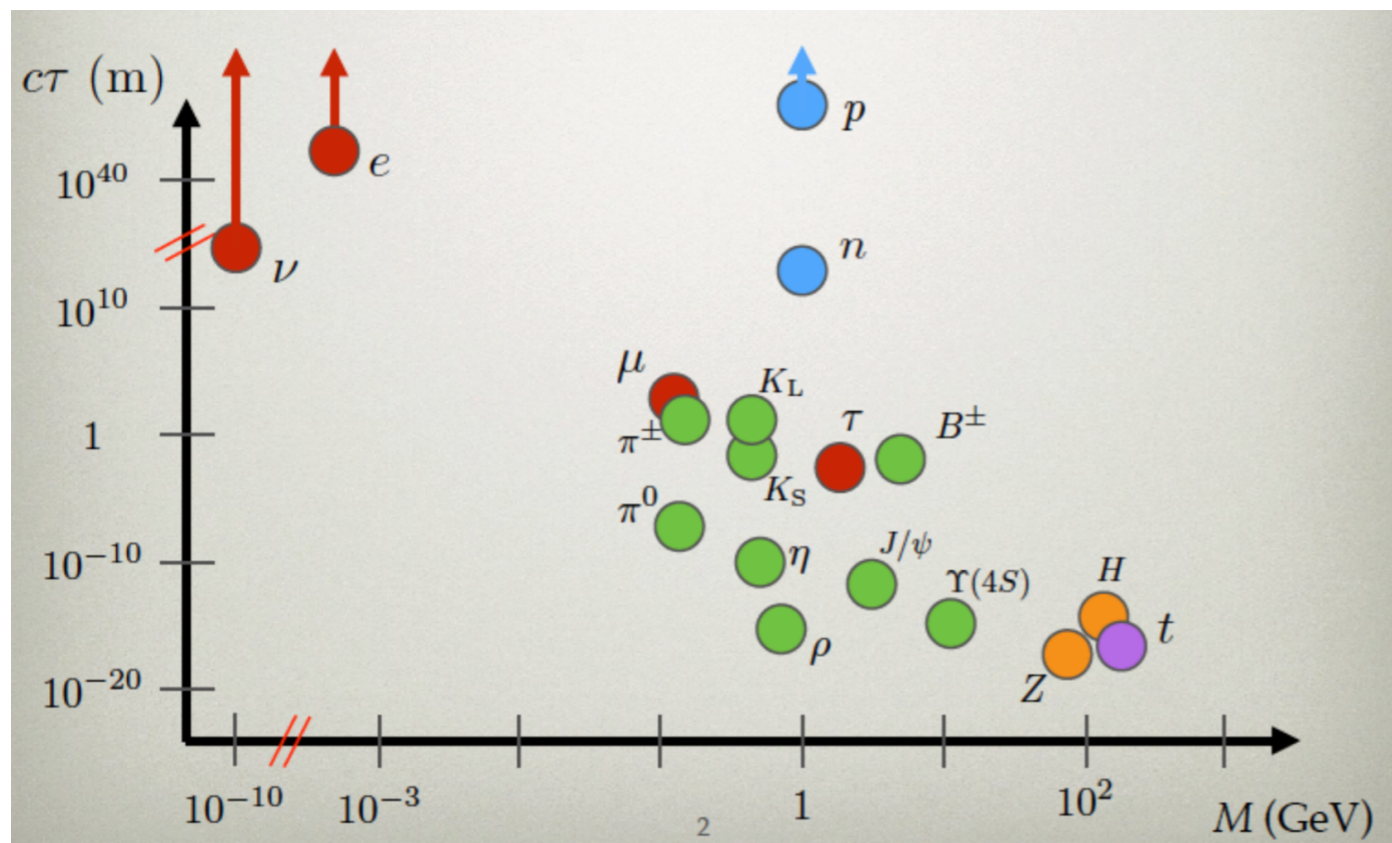BSM Models: Supersymmetry, dark QCD, RH neutrinos , Neutral Naturalness, Higgs Portal, Z' Portal, Hidden Valleys, …

LLP signatures-> arXiv:1903.04497 ; LLP theory motivations-> arXiv 1806.07396

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Dark Matter is an important pillar for the LLP@LHC programme

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Muon Collider

- Renewed interest in Snowmass. MuC has its own joint forum across the EF, AF and TG (see A. Tricoli's kick-off talk Monday, unstructured discussion on Tuesday, Snowmass Muon Collider Forum, https://indico.fnal.gov/event/50346/)

- AF: See review talk by Srudhara Dasu on Tuesday.

- Many interesting (and diverse) physics opportunities!

  - Review: Muon Smasher's guide (Al Ali et al, 2103.14043),

  - Higgs: see Z. Liu's talk on Wednesday (and refs therein)

  - EW: Buarque et al, 2106.01393

  - Top Physics: T. Theil's talk on Wednesday (and 2010.05915)

  - BSM: Franceschini, Greco, 2103.01617

  - LQs: C. Cesarotti et al (talk on Thursday, 2104.05720),

  - RK (LQs + Z'): G.Y. Huang et al, 2103.01617

  - Higgs self-coupling: T. Han et al, 2108.05362

  - Dark Matter: Costa's talk this session (also arXiv 2107.09688)

  - … more to come! (and also those I omitted)
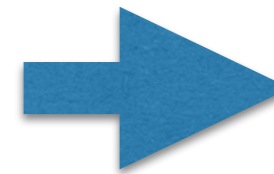
LLPs@MuC

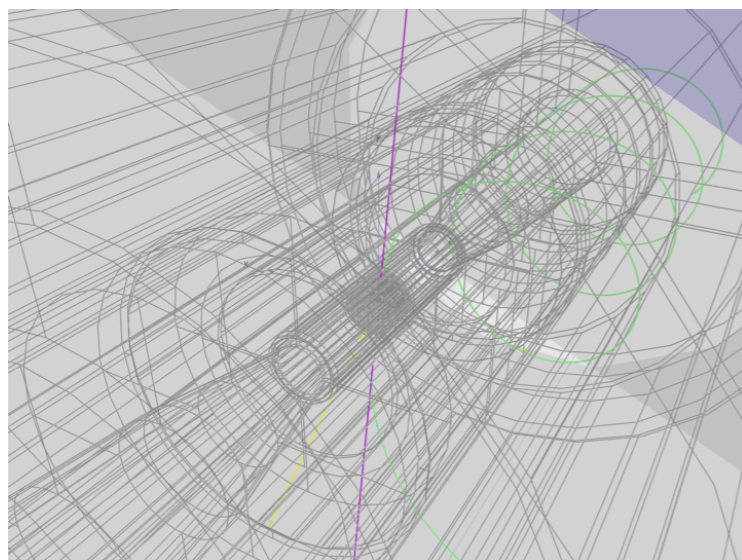- Which advantages can a MuC give for LLPs? Folklore: "A lepton collider is clean..."

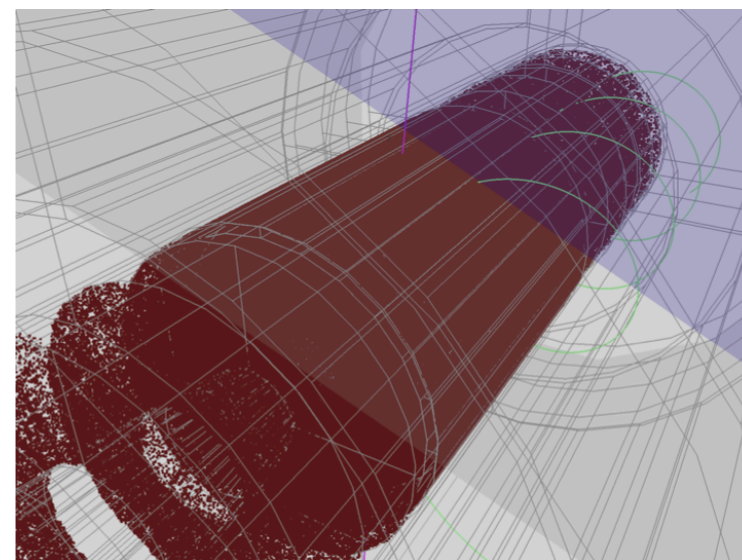- MuC is not clean for LLPs (~4×10^5 μ/m, give or take...).

Beam-Induced Background (BIB)

signal event display

BIB off

BIB on

Credit: F. Meloni
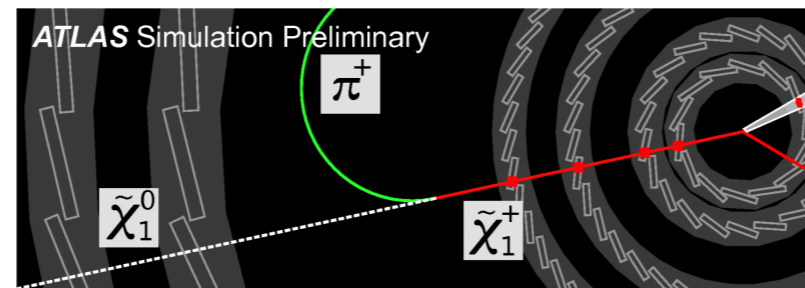
TeV "pure" Electroweakinos: MSSM's last stand

- The neutralino is the MSSM DM candidate, made out of Bino, Wino and Higgsino*.

- Relic density sets "pure" masses: $\tilde{B}$(100 GeV), $\tilde{W}$ (2.7 TeV), $\tilde{H}$ (1.1 TeV).

Since EW symmetry is broken, in an EW multiplet neutral components correct their masses due to Z-loops, charged components also have W, γ-loops.

Y	$c\,\tau$ [mm]	Δ_+ [MeV]
0	6.6	160
1/2	68	340

At pp colliders π⁺ gets <u>lost in hadronic noise</u>. The signature is a charged track (χ⁺) decaying into missing energy (χ⁰): *disappearing track.*

$$\chi^{\pm} \to \chi^0 + \pi^{\pm}$$

ATLAS Simulation Preliminary
π^+
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^+$

Popular benchmark: studied for several future colliders (see European Strategy Physics Briefing Book, 1910.11775)

* A pure Higgsino, EW doublet, is ruled out, because both neutral states are mass degenerate, and the Z-n1-n2 coupling is actually Z-n1-n1. Z currents with weak couplings are excluded by direct detection experiments (XENON100, LUX, etc). Some additional Bino and/or Wino component is required.
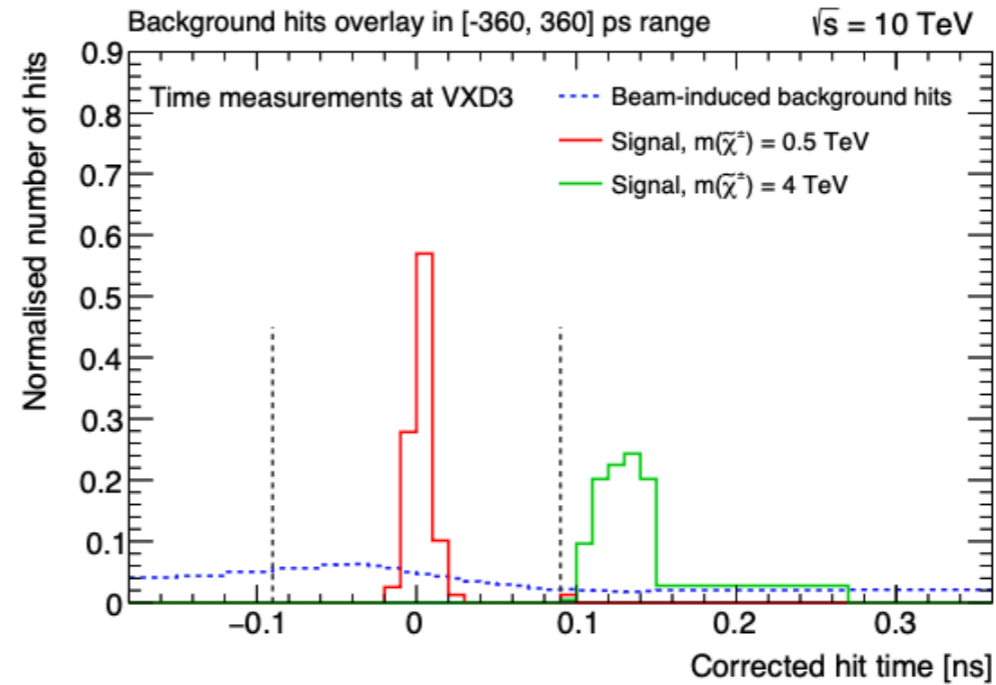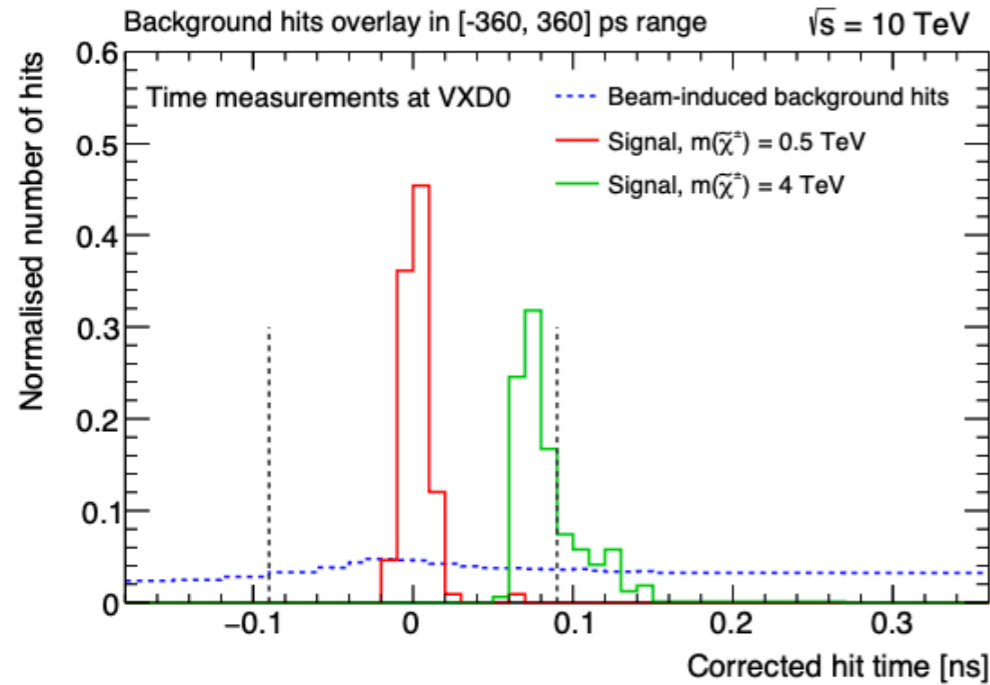
DTs@MuC

- MuC vs FCC-hh: Pair production of EWkinos is more central and less spread.

- About 10K events $\chi^\pm \chi^\mp$ at MuC 10 (MuC 3 has 1/10 less luminosity, 10 XS).
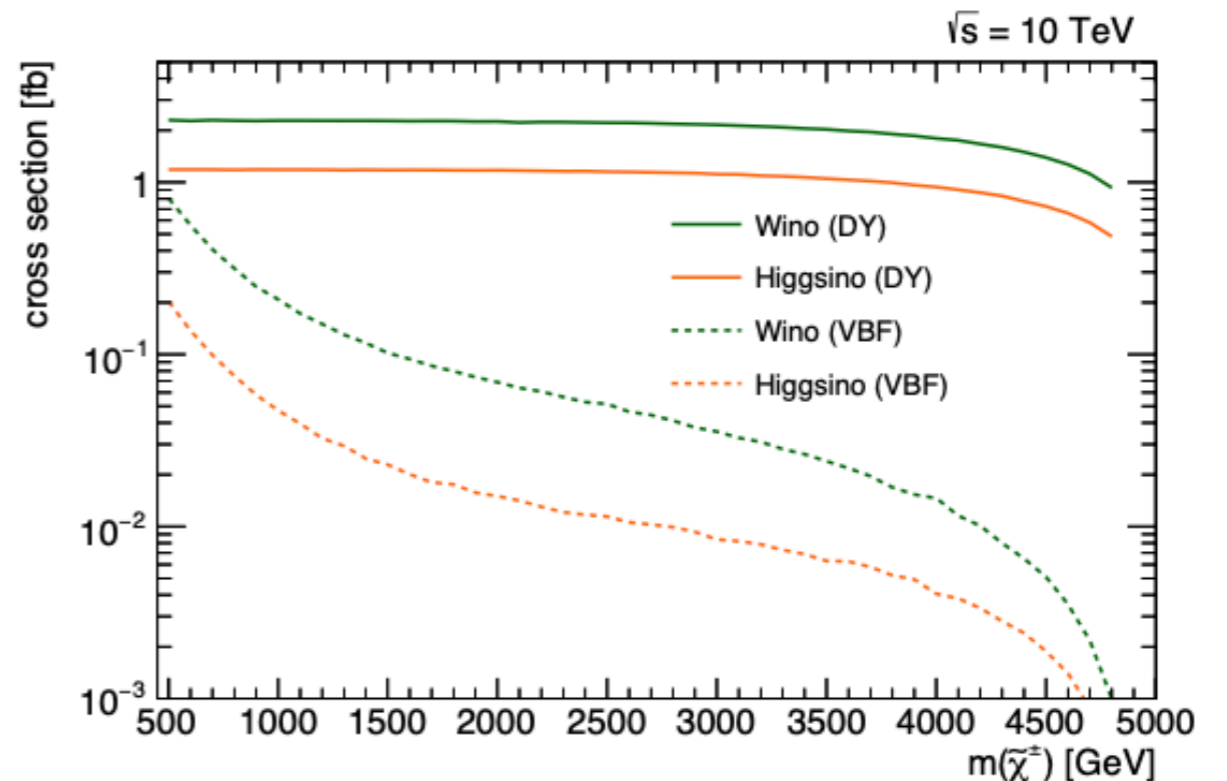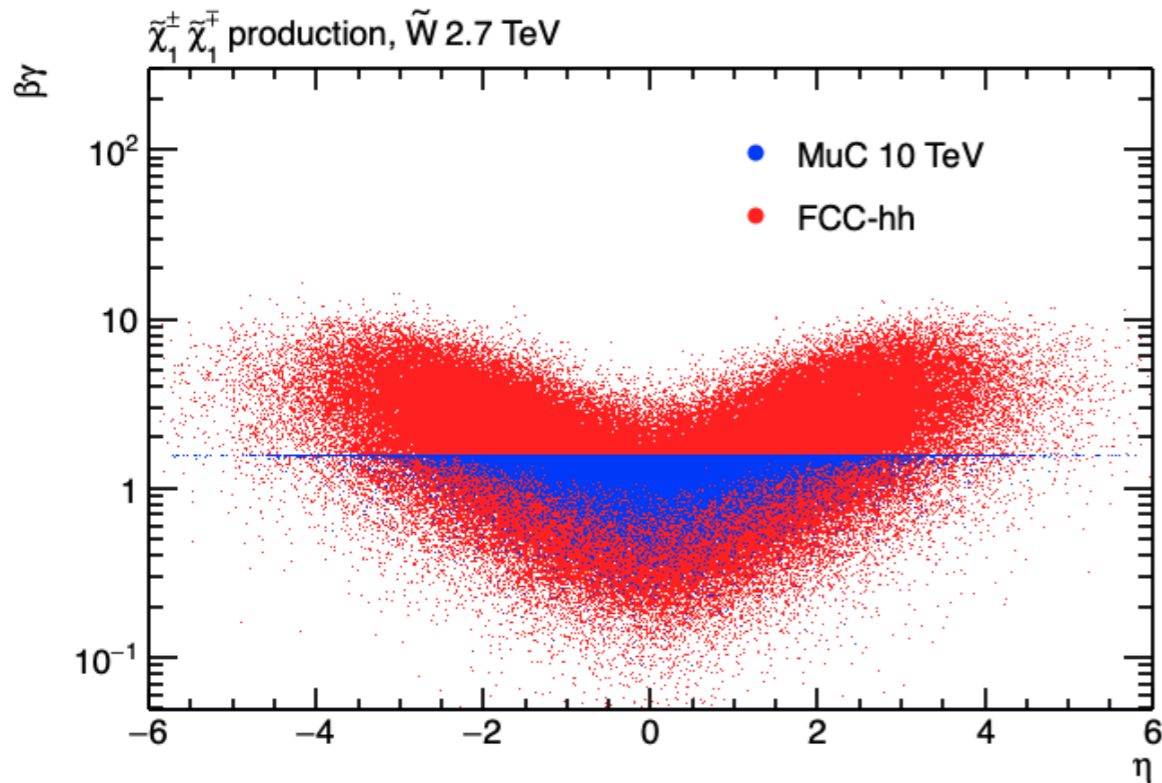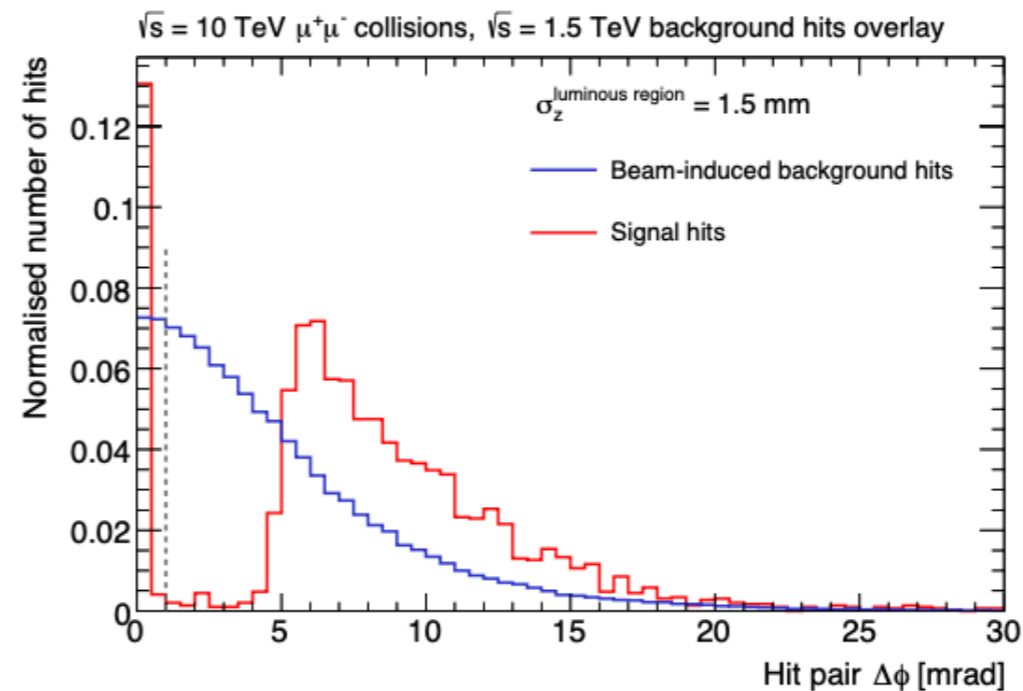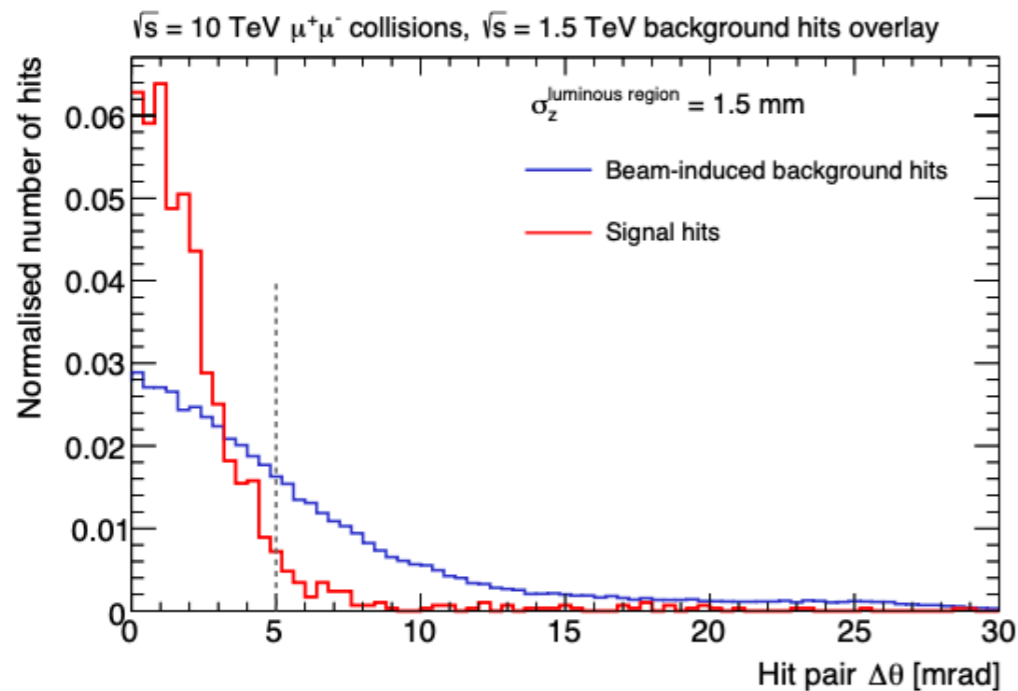

- Existing BIB simulation at 1.5 TeV CME (conservative estimate). 3 step plan:

  - #1: Reduce hits by a) timing and b) spatial correlations in double layer hits.

  - #2: Perform tracking imposing quality criteria (d0, good track fit, no holes).

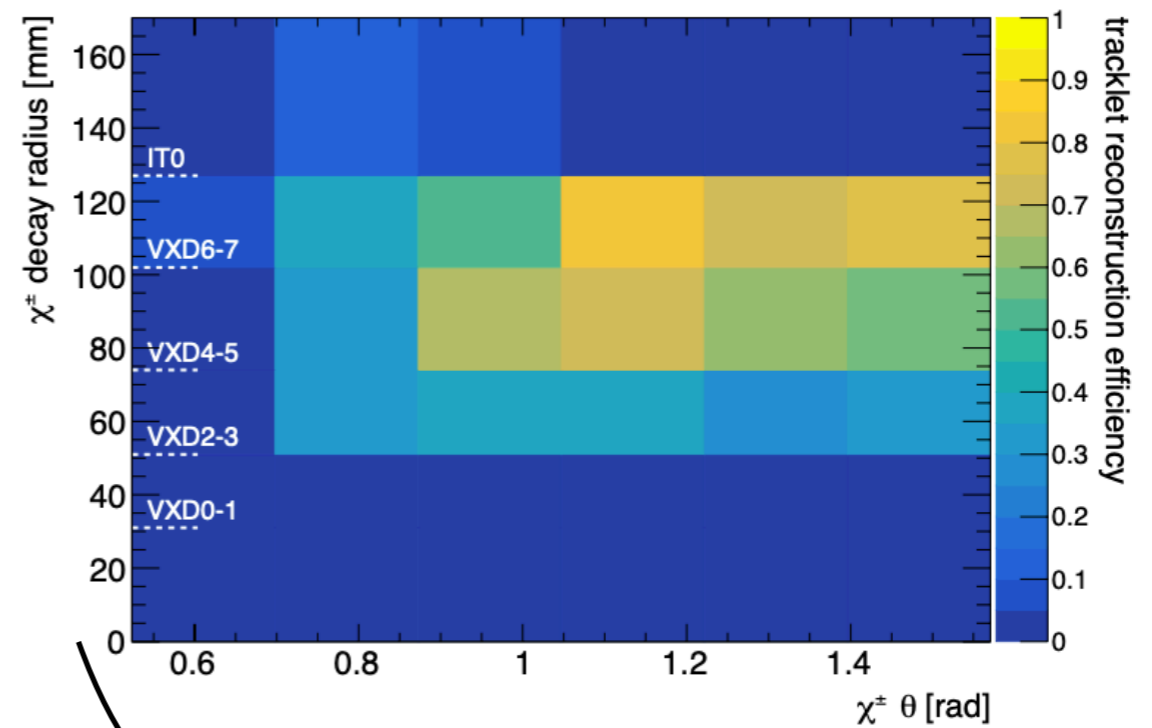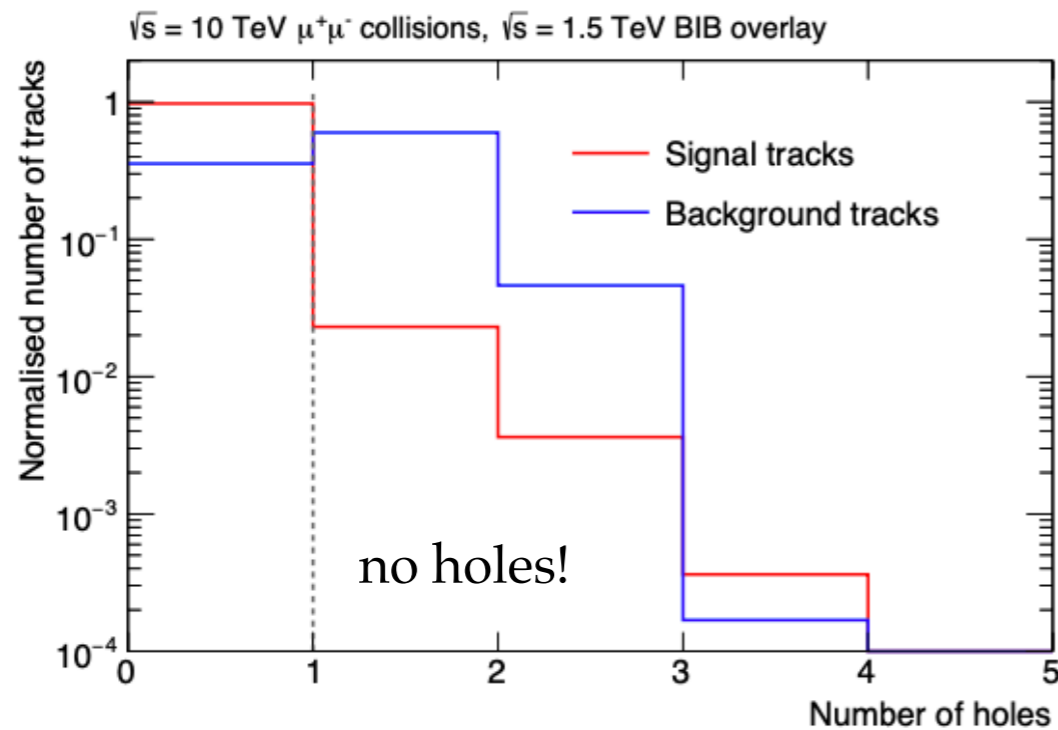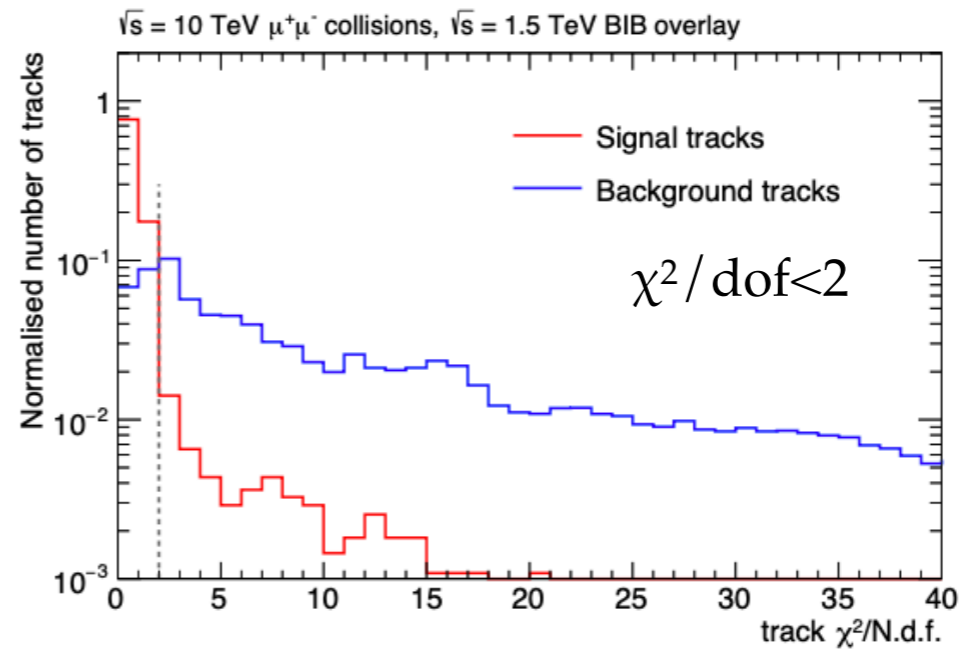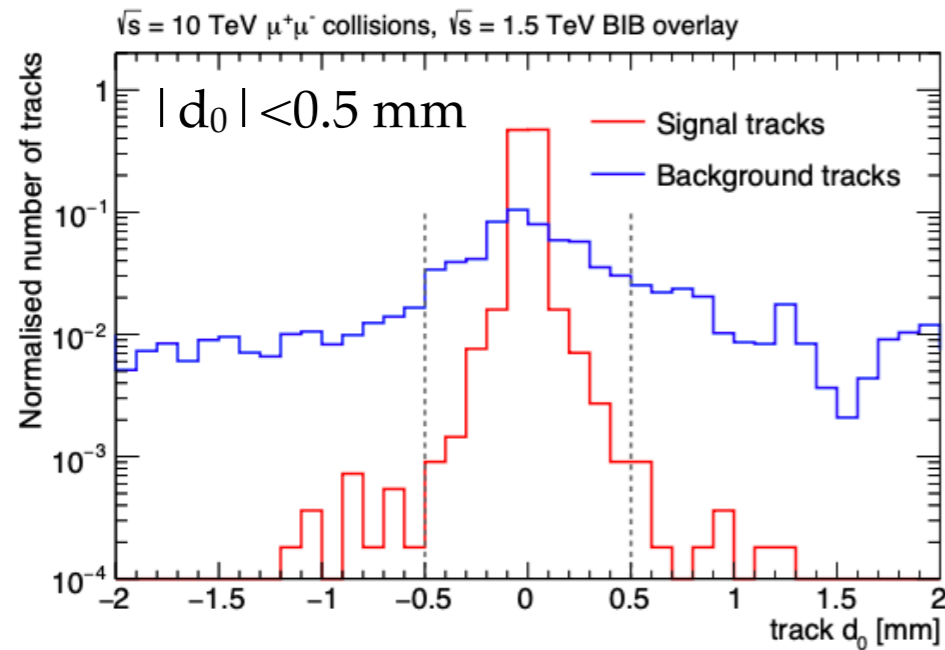 - #3: Collider analysis.

Reducing hits

Heavy particles can get lost!

Signal hits should be aligned!

Tracking

$\sqrt{s}$ = 10 TeV $\mu^+\mu^-$ collisions, $\sqrt{s}$ = 1.5 TeV BIB overlay

$|d_0| < 0.5$ mm

Signal tracks
Background tracks

Normalised number of tracks

track d_0 [mm]

$\sqrt{s}$ = 10 TeV $\mu^+\mu^-$ collisions, $\sqrt{s}$ = 1.5 TeV BIB overlay

$\chi^2/\mathrm{dof} < 2$

Signal tracks
Background tracks

Normalised number of tracks

track χ^2/N.d.f.

$\sqrt{s}$ = 10 TeV $\mu^+\mu^-$ collisions, $\sqrt{s}$ = 1.5 TeV BIB overlay

Signal tracks
Background tracks

no holes!

Normalised number of tracks

Number of holes

$\chi^\pm$ decay radius [mm]

IT0
VXD6-7
VXD4-5
VXD2-3
VXD0-1

tracklet reconstruction efficiency

$\chi^\pm$ θ [rad]

Tracklet efficiency
(model-independent)

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Collider analysis (I)

2 Signal Regions

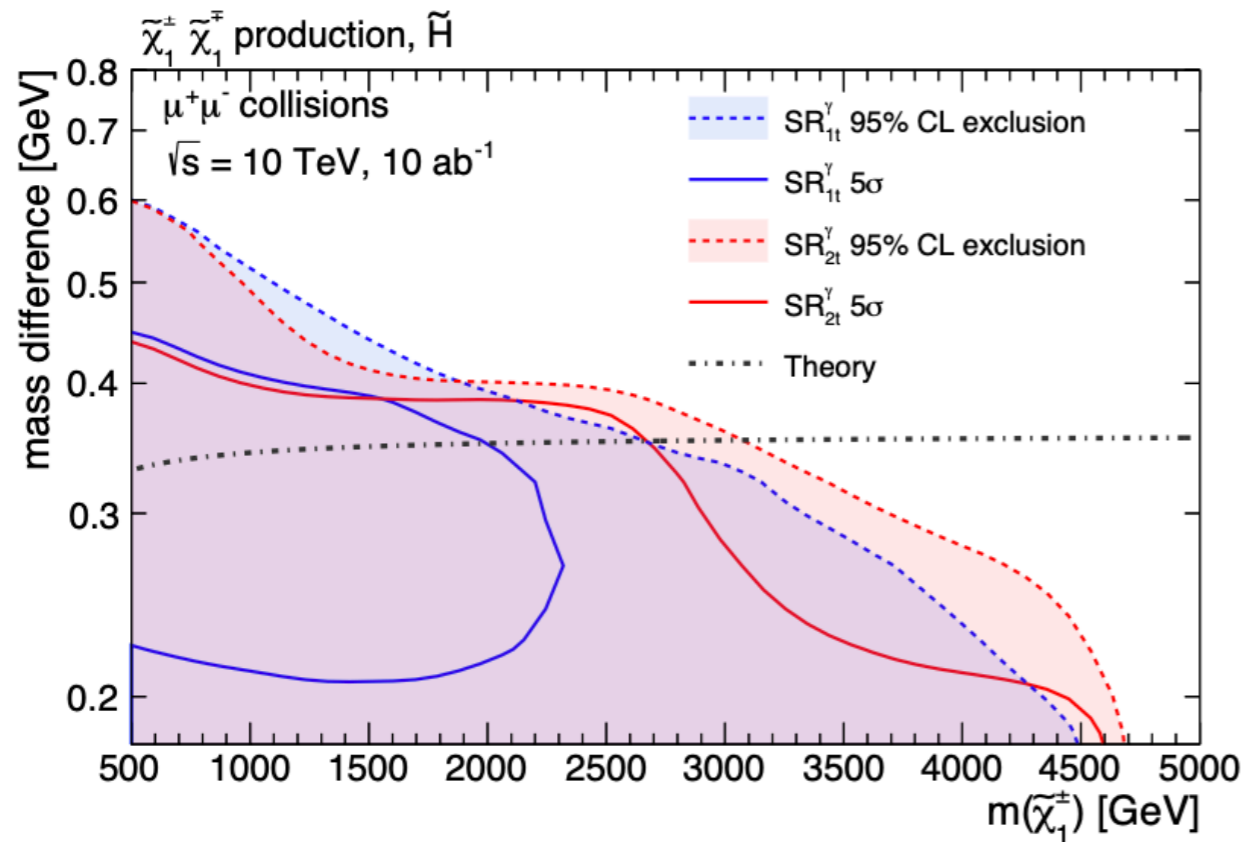| Requirement / Region	SR_{1t}^{γ}	SR_{2t}^{γ}
Vetoes	leptons and jets	
Leading tracklet p_T [GeV]	> 300	> 20
Leading tracklet θ [rad]	$[2/9\pi, 7/9\pi]$	
Subleading tracklet p_T [GeV]	-	> 10
Tracklet pair Δz [mm]	-	< 0.1
Photon energy [GeV]	> 25	> 25

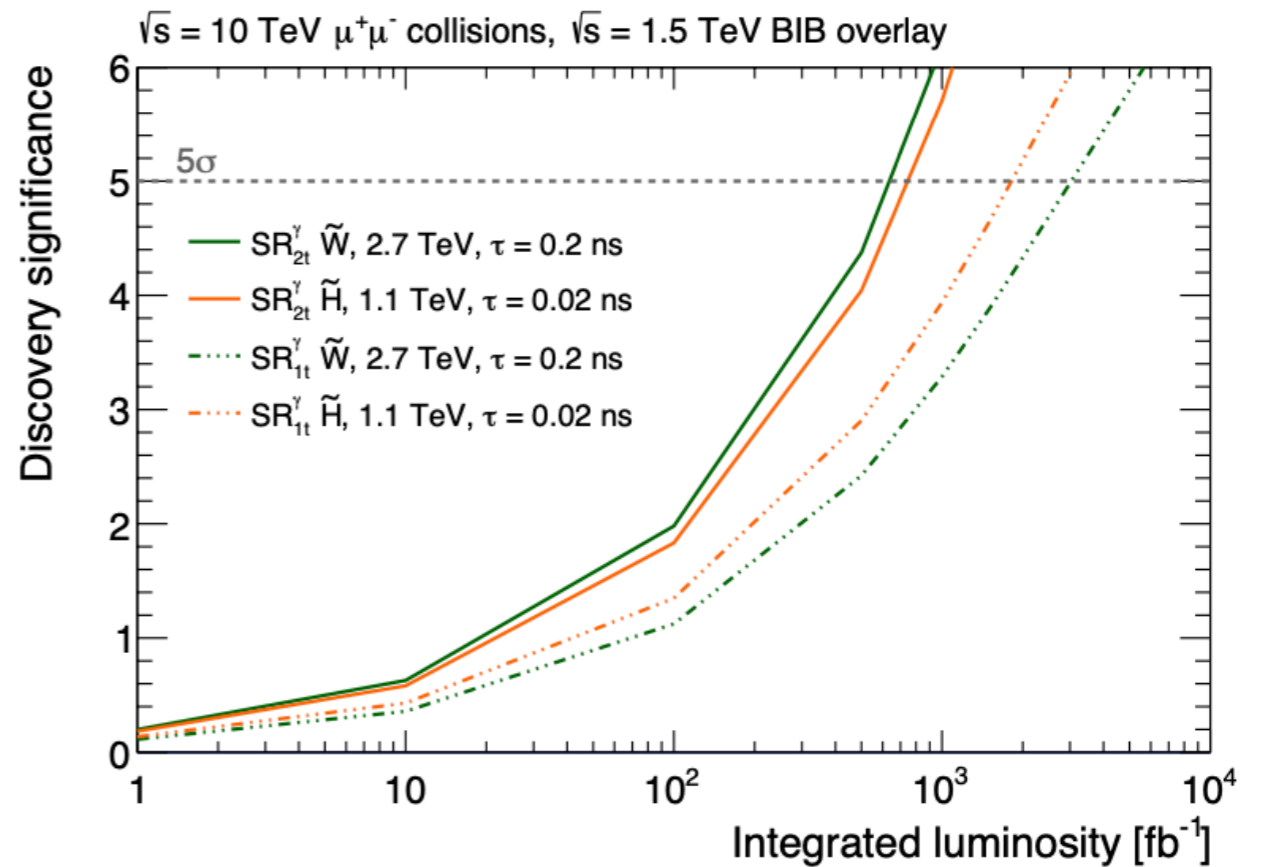|	SR_{1t}^{γ}	SR_{2t}^{γ}
Total background	187.8 ± 0.6	0.16 ± 0.05
$\tilde{W}$, 2.7 TeV, $\tau = 0.2$ ns	201 ± 5	199 ± 4
$\tilde{H}$, 1.1 TeV, $\tau = 0.02$ ns	253 ± 4	170.5 ± 2.1

Right relic abundance

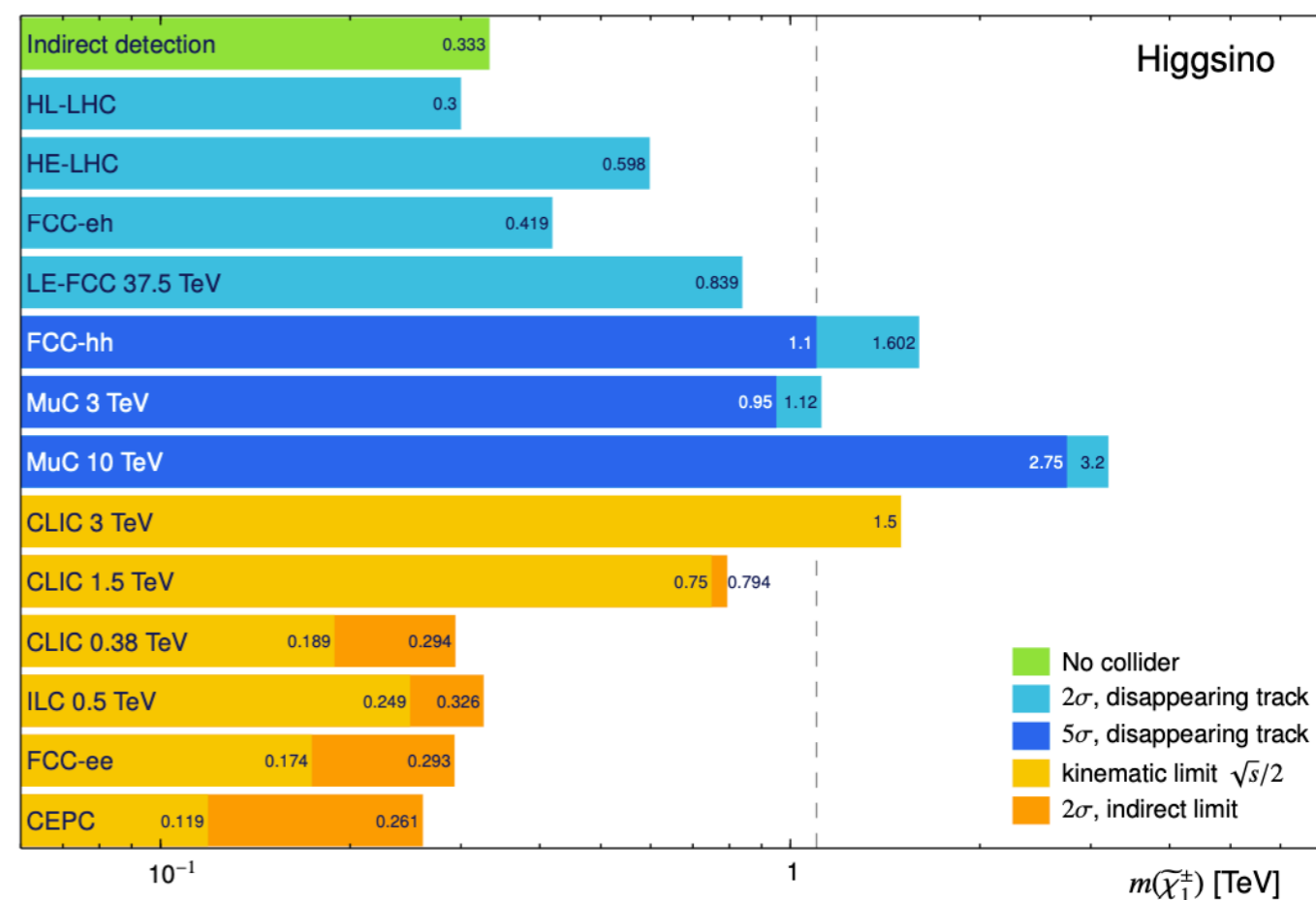non-zero | morally 0
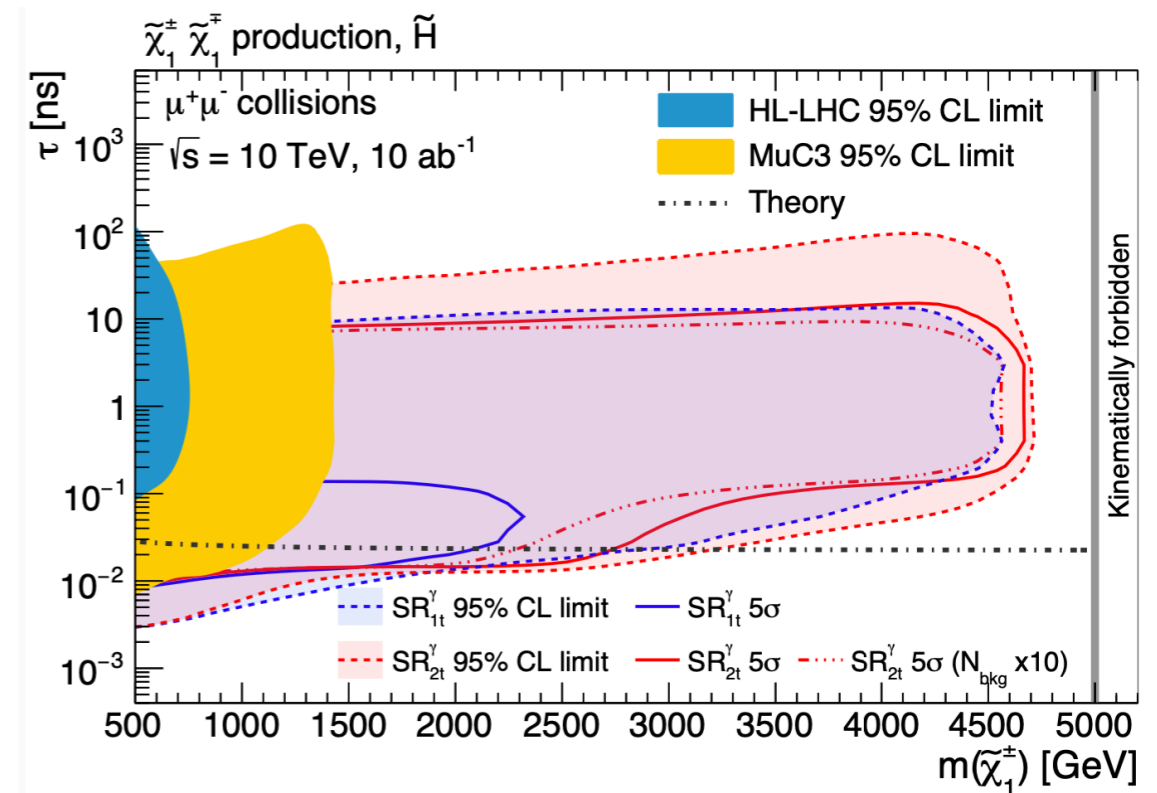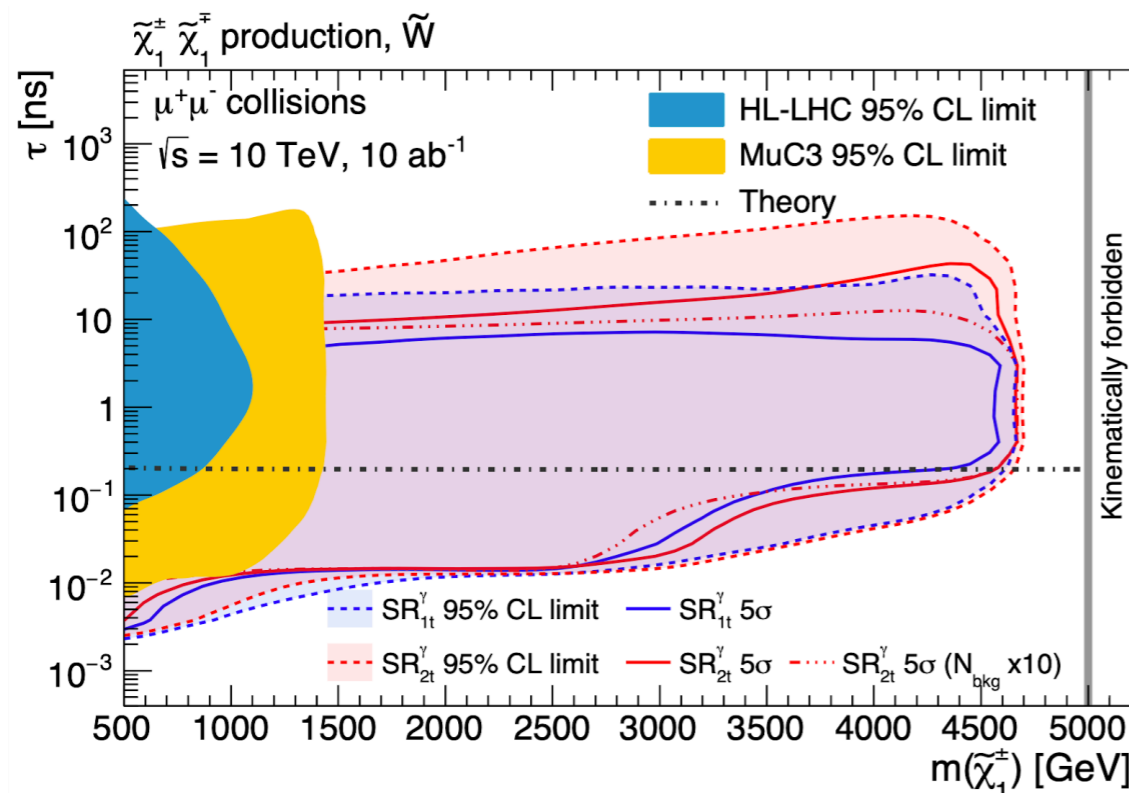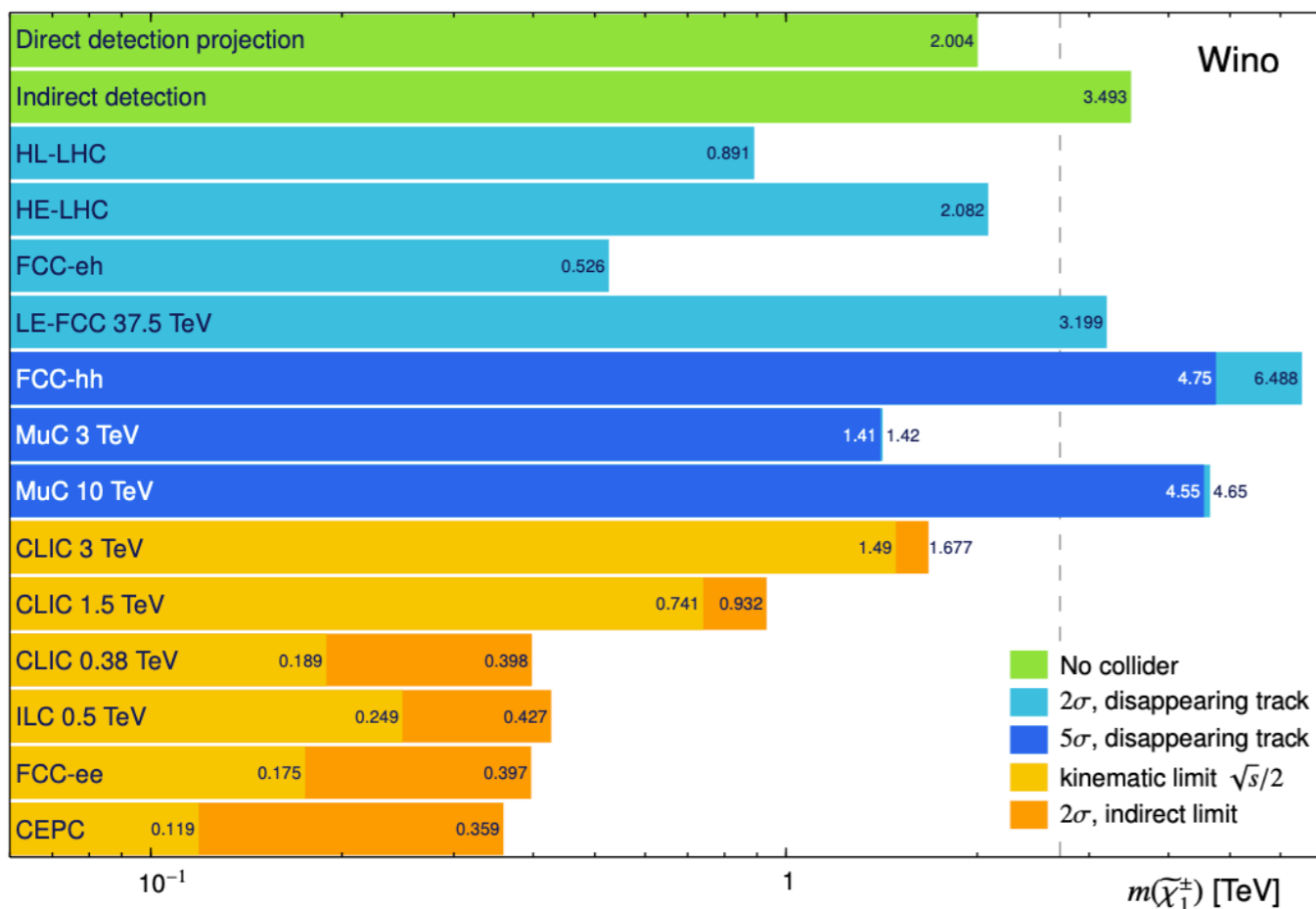
Collider analysis (II)

Mass reach reduces fast with Δ

About 0.5/ab for discovery
(0.1 for exclusion)

Comparison with other colliders

- MuC toe-to-toe with FCC-hh (can cover both thermal Higgsinos and Winos)
- Warning! Do not overbuy benchmarks

  (worth checking non-MSSM WIMPs and non-WIMP scenarios as well!)

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Outlook

- Muon Collider (MuC) is at the forefront of the Snowmass effort. Many promising physics opportunities arise, cross-frontiers (EF-AF-TF).

- Long-Lived Particles (LLPs), a theoretically sound BSM class of signatures, can be well explored at a MuC.

- This talk: disappearing tracks (a LLP signature) can lead to discovery of thermal Winos and Higgsinos (de-facto benchmark for future colliders).

- Beneficial: consider other models (non-SUSY, non-WIMPs) using DT@MuC.

- For MuC folks: It would be highly desirable to have an updated Beam Induced Background (BIB) sample to verify the assumption that (fixing the "machine") the BIB decreases with energy. This is needed for a robust assessment of the MuC experimental sensitivity (particularly for LLPs).

- Other LLP signatures are a low-hanging fruit (DVs, HSCPs, etc…). MuC is not clean out of the box, but can be made cleaner [taming BIB].

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